ON QUADRATIC RESIDUES*

BY

J. McDONNELL

1. Let m be any integer, n a positive odd integer, and s a primitive nth root of unity. We shall prove that the product

$$A = \prod_{k=1}^{\frac{1}{2}(n-1)} \frac{s^{km} - s^{-km}}{s^k - s^{-k}}$$

is identical with Jacobi's symbol (m/n) and obtain a proof of the quadratic reciprocity theorem. If m and n have a common factor g, then $A = 0$, since the numerator of A has the factor $s^{qm} - s^{-qm} = 0$, where $q = n / g$.

2. We shall show that, when m and n are relatively prime, A is independent of the particular primitive root s employed. First, let m be positive and odd, and let r be a primitive mth root of unity. Since m is odd, the mth roots of unity are $1, r^2, r^4, \cdots, r^{2(m-1)}$. Hence

$$x^m - y^m \equiv (x-y)(xr - yr^{-1})(xr^2 - yr^{-2}) \cdots (xr^{m-1} - yr^{-(m-1)}),$$

identically. Take $x = s^q$, $y = s^{-q}$. We see that

$$A = \prod_{p=1}^{m-1} \prod_{q=1}^{\frac{1}{2}(n-1)} (r^p s^q - r^{-p} s^{-q}).$$

Similarly,

$$B = \prod_{k=1}^{\frac{1}{2}(m-1)} \frac{r^{kn} - r^{-kn}}{r^k - r^{-k}} = \prod_{p'=1}^{\frac{1}{2}(m-1)} \prod_{q'=1}^{n-1} (r^{p'} s^{q'} - r^{-p'} s^{-q'}).$$

To any factor $F = r^p s^q - r^{-p} s^{-q}$ in A there corresponds a factor

$$F' = r^{p'} s^{q'} - r^{-p'} s^{-q'}$$

in B such that one of the alternatives

(i) $\quad p = p', \quad q = q', \quad p \leqq \frac{1}{2}(m-1), \quad q' \leqq \frac{1}{2}(n-1),$

(ii) $p + p' = m, \quad q + q' = n, \quad p > \frac{1}{2}(m-1), \quad q' > \frac{1}{2}(n-1),$

holds. In the first case, $F = F'$; in the second, $F = -F'$. Hence

$$A = (-1)^{\frac{(m-1)(n-1)}{4}} B.$$

As B is independent of s, A is also.

* Presented to the Society (Chicago), March 21, 1913.

Next, let m be negative or even. Choose t so that $\mu = m + tn$ is positive and odd. The expression in § 1 for A remains unaltered if we replace s^m by s^μ. By the preceeding proof, A is independent of s.

Accordingly we can in all cases represent the function A by the symbol $f(m, n)$, since it depends upon m and n only.

3. We shall now show how to evaluate $f(m, n)$ by a process of reduction based upon the following three properties:*

$$(1) \qquad f(m, n) = f(p, n) \qquad \text{if } p \equiv m \pmod{n},$$

$$(2) \qquad f(p, n) = (-1)^{\frac{n-1}{2}} f(q, n) \qquad \text{if } p + q \equiv 0 \pmod{n},$$

$$(3) \qquad f(m, n) = (-1)^{\frac{(m-1)(n-1)}{4}} f(n, m) \text{ if } m \text{ and } n \text{ are positive and odd.}$$

Let p be the positive remainder $< n$ obtained by dividing m by n. Then $f(m, n) = f(p, n)$ by (1). If p is even, define the odd number q by $p + q = n$ and apply (2). Thus either p itself or else q is positive and less than n. We now apply (3). After repetitions of this process, we ultimately reach unity and an odd number l such that $f(m, n) = \pm f(1, l)$. But $f(1, l) = 1$ (§ 1). Thus $f(m, n) = \pm 1$ and the sign is determined by the reduction process.

4. If $m = pq$, then

$$(4) \qquad f(m, n) = f(p, n) \cdot f(q, n).$$

We may assume that m is relatively prime to n, since otherwise each member is zero by § 1. Then $s_1 = s^q$ is a primitive nth root of unity and

$$\frac{s^{km} - s^{-km}}{s^k - s^{-k}} = \frac{s_1^{kp} - s_1^{-kp}}{s_1^k - s_1^{-k}} \cdot \frac{s^{kq} - s^{-kq}}{s^k - s^{-k}},$$

from which (4) follows. In particular,

$$(5) \qquad f(m, n) = \{f(2, n)\}^p \cdot f(q, n), \qquad \text{if } m = 2^p q \qquad (q \text{ odd}).$$

By (2) and (3),

$$f(2, n) = (-1)^{\frac{n-1}{2}} f(n-2, n), \qquad f(n-2, n) = f(n, n-2),$$

* The third property was proved in § 2. The first and second follow from

$$s^{kp} = s^{km}, \qquad s^{kq} - s^{-kq} = -s^{kp} + s^{-kp}.$$

since $(n-1)(n-3) \equiv 0 \pmod 8$. Then, from these and (1),

$$f(2, n) = (-1)^{\frac{n-1}{2}} f(2, n-2). \tag{6}$$

If ω is an imaginary cube root of unity,

$$f(2, 3) = \frac{\omega^2 - \omega^{-2}}{\omega - \omega^{-1}} = -1.$$

Then, by (6), $f(2, 5) = -1$, $f(2, 7) = 1$, $f(2, 9) = 1$, and, generally,

$$f(2, n) = (-1)^{\frac{n^2-1}{8}}. \tag{7}$$

5. If $n = ab$, as in any text on the theory of numbers,

$$\frac{n^2-1}{8} \equiv \frac{a^2-1}{8} + \frac{b^2-1}{8}, \qquad \frac{n-1}{2} \equiv \frac{a-1}{2} + \frac{b-1}{2} \pmod 2.$$

Hence by (7) and (3), with m replaced by an odd number q,

$$f(2, n) = f(2, a) \cdot f(2, b), \qquad f(q, n) = f(q, a) \cdot f(q, b).$$

The extension to the case in which n is the product $abc \cdots$ of several factors is evident. Hence, using (5), we get

$$f(m, n) = f(m, a) \cdot f(m, b) \cdot f(m, c) \cdots. \tag{8}$$

6. Let x be the product of the factors in the numerator of A (§ 1) and y the product of those in the denominator of A. Set $\eta = (-1)^{\frac{(n-1)(n-3)}{8}}$. As shown by Gauss,*

$$\eta x = 1 + s^m + s^{4m} + \cdots + s^{m(n-1)^2}, \qquad \eta y = 1 + s + s^4 + \cdots + s^{(n-1)^2}.$$

First, let n be a prime, and let α range over the quadratic residues $(< n)$ of n, and β over the non-residues. Then

$$\eta y = 1 + 2\Sigma s^\alpha, \qquad \eta x = 1 + 2\Sigma s^\alpha \quad \text{or} \quad 1 + 2\Sigma s^\beta,$$

according as m is a quadratic residue or non-residue. Hence

$$x = y, \qquad f(m, n) = x / y = 1,$$

if m be a residue of n; while if m be a non-residue,

$$\eta(x + y) = 2(1 + \Sigma s^\alpha + \Sigma s^\beta) = 0, \qquad f(m, n) = -1.$$

Hence, if n is a prime, $f(m, n)$ is identical with Legendre's symbol (m/n).

Next, let $n = abc \cdots$, where $a, b, \cdots$ are primes. Then, by (8),

$$f(m, n) = \left(\frac{m}{a}\right)\left(\frac{m}{b}\right)\left(\frac{m}{c}\right)\cdots.$$

Thus $f(m, n)$ is identical with Jacobi's symbol (m/n).

* *Disquisitiones arithmeticae,* German translation by MASER, 1889, p. 474.